

Precision Synchronization for Long-distance Free-space Quantum Networking

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Abstract: We describe a laboratory implementation of a precision synchronization technique suitable for high-rate entanglement distribution between two ground sites via a satellite, including recent improvements for extending the technique to larger Doppler ranges. © 2023 Massachusetts Institute of Technology

Realizing a technique for precision synchronization of short optical pulses is important for enabling practical high-rate long-distance quantum entanglement distribution. Because the flux of entangled photons sent between locations is generally insufficient to support a control loop bandwidth sufficient to align signals, it becomes necessary to include additional synchronization photons. The engineering details of a synchronization control approach depend on a large set of considerations such as location of sources (space or ground), satellite orbits, aperture sizes and link budgets, source photon duration, and laser tunability. References [1,2] describe two techniques suitable for different architectural approaches. In [2], we presented a technique for the synchronization of short (~ 1 ps) optical pulses used in a dual-uplink architecture in which two ground terminals generate shared entanglement via the interaction of entangled photons received at the satellite. This architecture is compelling in that much of the size, weight, and power burden falls to the ground terminals, while resources needed on the satellite are kept relatively simple. This paper summarizes recent improvements to the laboratory synchronization testbed described in [2] to enable the technique to function and be tested over realistic Doppler ranges and rates.

Figure 1 shows a schematic representation of the testbed. See [2] for additional details. The pulse repetition rates (PRRs) of two high-rate entangled photon sources are fixed to ~ 1 -GHz frequency-tunable synthesizers using analog phase-locked loops (PLLs) at each of the sources. A space-to-ground digital PLL uses a relative timing alignment measurement generated at the satellite for frequency control of the reference synthesizers at the ground stations. This frequency adjustment can correct for Doppler effects arising from the satellite motion, and, because phase is the integral of frequency, it also accomplishes the fine timing alignment of the two signals. A Hong-Ou-Mandel (HOM) interferometer [3] provides the sensitive relative timing discriminant, as described in [2].

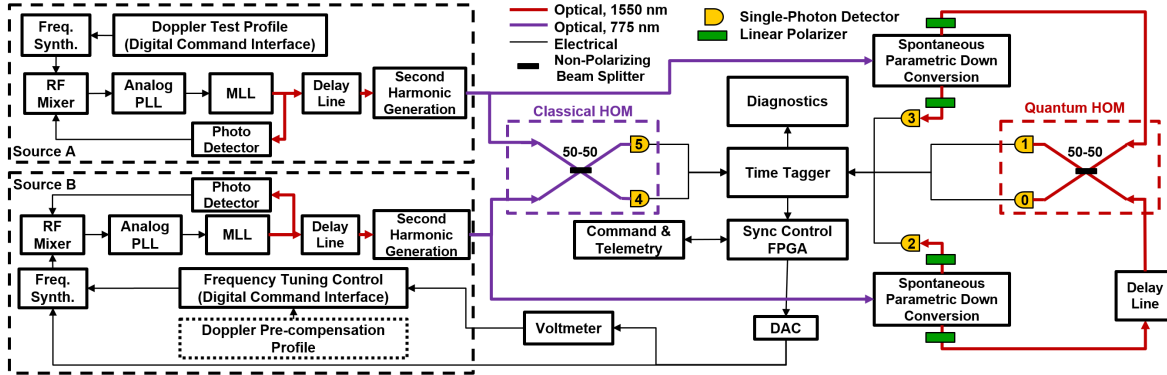


Fig. 1. Experimental configuration (see Ref [2] for additional details). Photons from a 1550-nm mode-locked laser (MLL) generate entangled photon pairs and a 775-nm synchronization signal. The synchronization signals from two such sources (A and B) interact in a HOM interferometer, from which coincidence counts are processed in real time with a time tagger and a field-programmable gate array (FPGA). A digital PLL generates a feedback control signal to the source-B synthesizer via a 16-bit digital-to-analog converter (DAC) which is updated every 10 ms with a type-3 PLL. A digital control interface is used to set the Source-A frequency to follow a pre-programmed profile. A control computer monitors the DAC voltage via a voltmeter, and generates a digital command to counter-tune the Source-B synthesizer to maintain the DAC within its range.

While [2] demonstrated the essentials of the space-to-ground control loop, it is important to extend the technique in Doppler range and rate in order to be useful for the dual-uplink application. The space-to-ground propagation delay fundamentally limits the feasible loop bandwidth, and leads to the use of a type-3 control loop that can in principle null out the phase error resulting from a frequency offset and a frequency rate of change, with the residual phase error set by the frequency curvature. Depending on the orbit of interest, the lasers and control electronics must be able to rapidly and precisely tune over a wide (up to $\sim \pm 23$ parts/million) range at rates up to ~ 400 parts/billion/s. To fully test the capability, one source is deterministically adjusted to represent the Doppler effects that the satellite motion would

create, while the other source is tuned by the PLL to maintain synchronization. With a capability to tune sources over these ranges and rates, the testbed would be able to perform realistic tests while demonstrating full control loop tracking capability as well as include the groundwork for a Doppler pre-compensation capability that will be important both for reducing or shifting the control ranges needed at a specific source, and for realizing fast acquisition.

The work reported here makes progress toward the above goals in three areas: 1) providing testbed source PRR control with both the range and precision needed to accurately test realistic Doppler motion; 2) demonstrating a method for ‘relaxing’ the tracking loop DAC to support operation over a range larger than would otherwise be possible with the limited 16-bit DAC range; 3) demonstrating the essentials needed for Doppler pre-compensation. Item 1) is achieved by controlling the source-A synthesizer with digital frequency commands that specify a Doppler profile with tailorable range, rate, and curvature. Item 2) is achieved by implementing an algorithm that observes the changes in the DAC and counter-tunes the synthesizer so that the DAC does not exceed its range. For the data shown below, a separate voltmeter measured the DAC voltage for use by a software control loop which could counter-tune the synthesizer via a precise digital interface. While not directly tested, the potential utility of Doppler pre-compensation in item 3) is visible in the data below in that the counter-tuning profile generated by item 2) would have a similar effect if there were a pre-programmed tuning profile representing the expected Doppler.

Fig. 2 shows the testbed synchronization measurements. A Doppler test profile (2a) is generated at the Source-A controller. The time and ranges can be set to test particular Doppler ranges, rates, and curvatures. While during a horizon-to-horizon session to a satellite the frequency would move in only one direction, symmetric test profiles are used for convenience. The DAC (2b) moves over a range corresponding to 2.4 Hz (~600 DAC steps) vs. the 83 Hz Doppler range. This occurs due to the compensation loop that measures the DAC output voltage and counter-tunes the synthesizer. (2c) shows recorded control telemetry of the frequency offset generated by the control loop in real time and used to digitally command the Source-B synthesizer, which is simultaneously tuned through an analog frequency modulation port using the DAC voltage. As expected, this closely matches the test profile (2a), with the small difference being reflected by (2b). (2d) shows the HOM coincidence counts and a running ~1-s average, indicating that the photons from the two sources are aligned to better than ~1 ps. (2e) shows the reduced rate of change experienced by the FPGA because of the off-loaded control provided by the outer loop.

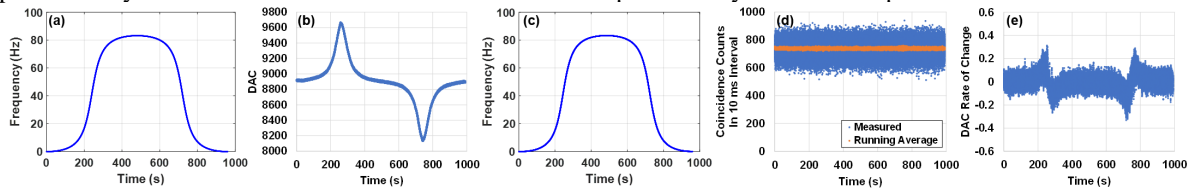


Fig. 2. Synchronization test results. (a) Doppler tuning profile used to sweep Source-A MLL PRR over 83 Hz with a maximum rate of change of 0.8 Hz/s and a curvature of 0.013 Hz/s². (b) Source-B control FPGA 16-bit DAC control setting telemetry. (c) Source-B counter-tuning telemetry recorded by the frequency tuning software control loop. (d) Telemetry showing the coincidence counts measured in a 10-ms control interval (blue) and a ~1-s running average (orange). The relative timing of the two sources is maintained to <1 ps with coincidence counts held stably on the side of the HOM dip. (e) Recorded DAC rate of change (DAC steps per 10 ms control interval), showing a reduced rate of change experienced by the control-FPGA due to the counter-tuning software control loop. Source tunes by ~4 mHz for each DAC step.

This paper has described ongoing development of a space-to-ground synchronization technique suitable for long-distance high-rate quantum networking. The work here has taken steps toward extending the testbed capability to be suitable for testing over larger Doppler ranges, has implemented a technique for extending the tracking loop range of operation beyond the range of a 16-bit DAC by counter-tuning a synthesizer in response to changes in the DAC, and in doing this has demonstrated the essentials of a Doppler pre-compensation technique. Further work is planned to demonstrate the hardware and control algorithm capability over a much wider Doppler range while utilizing Doppler pre-compensation.

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References

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